

APPLICATION  
FOR REISSUE OF  
UNITED STATES LETTERS PATENT  
NUMBER 5,473,526

TITLE: SYSTEM AND METHOD FOR POWER-EFFICIENT CHARGING  
AND DISCHARGING OF A CAPACITIVE LOAD FROM A SINGLE  
SOURCE

APPLICANT: LARS SVENSSON, WILLIAM C. ATHAS AND JEFFREY G.  
KOLLER

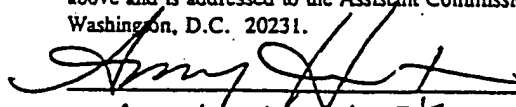
10040-1255200

BEST AVAILABLE COPY

"EXPRESS MAIL" Mailing Label Number  
Date of Deposit

EM36776194805  
12/5/97

I hereby certify under 37 CFR 1.10 that this correspondence is being  
deposited with the United States Postal Service as "Express Mail Post  
Office To Addressee" with sufficient postage on the date indicated  
above and is addressed to the Assistant Commissioner for Patents,  
Washington, D.C. 20231.

  
Amy M. Hunt

1

SYSTEM AND METHOD FOR  
POWER-EFFICIENT CHARGING  
DISCHARGING OF A CAPACITIVE LOAD  
FROM A SINGLE SOURCE

BACKGROUND OF THE INVENTION

1. Field of the Invention

The present invention relates to electronic circuits and systems. More specifically, the present invention relates to power dissipation in electronic circuits and systems.

2. Description of the Related Art

Power dissipation of electronic circuitry is an important design consideration for many applications. Power dissipation provides a measure of the efficiency of the system. The efficiency of the system impacts the design of the power supply for the system. That is, low efficiency leads to higher costs due to the waste of energy and the need for larger power supplies.

For battery powered systems, power dissipation limits battery life. This necessitates larger batteries which increases the cost and weight of the system while limiting the applicability thereof. As an example, consider coronary pacemakers where power dissipation is a critical concern due to the difficulty of accessing the battery for replacement and the cost and inconvenience associated with the use of larger batteries.

In addition, the dissipated energy is released in the form of heat. Accordingly, systems which exhibit considerable power dissipation often require measures such as heat sinks to protect or cool system components from the heat created by the circuit. The use of heat sinks and the like adds to the cost, size and weight of the system and thereby limits the utility of same.

For the CMOS (complementary-metal-oxide semiconductor) based system, used widely in the design of computers, digital logic circuits and the like, capacitive effects are primarily responsible for the dissipation of power. Such capacitive effects arise due to junction capacitances within semiconductor devices, interlead capacitances between lines connecting the circuit to external devices and the capacitance of a load.

In accordance with conventional teachings, power dissipation is directly related to the operating frequency ( $f$ ), the capacitance ( $C$ ) and the square of the voltage ( $V^2$ ) applied to the capacitive element.

In addition to the elimination of unnecessary capacitances and the reduction of the switching frequency to the lowest value that supports the functional specification of the circuit, most prior approaches to the problem have focused on reducing the voltage applied to the capacitive elements. However, in addition to costly interfacing issues, attempts to lower the voltage of digital processors and the like have been limited by the fact that the trend is to higher processing speeds which cannot be attained at arbitrarily low operating voltages.

Thus, there is an ongoing need in the art for a system and technique for minimizing the power dissipated by a digital system.

SUMMARY OF THE INVENTION

The need in the art is addressed by the present invention which, in a most general sense, provides a system and method for efficiently charging and discharging a capacitive load from a single voltage source. The inventive system

"Express Mail" mailing label number EM7367761985

Date of Deposit 12/5/97

I hereby certify that this paper or fee is being deposited with the United States Postal Service "Express Mail Post Office to Addressee" service under 37 CFR 1.10 on the date indicated above and is addressed to the Commissioner of Patents and Trademarks, Washington, D.C. 20231

*James D. Lee*

BEST AVAILABLE COPY

0075554-0100

includes a first switch for selectively connecting the voltage source to the load and a second switch for selectively providing a short across the load as may be common in the art. A particularly novel aspect of the invention resides in the provision of plural capacitive elements and a switching mechanism for selectively connecting each of the capacitive elements to the load whereby the load is gradually charged or discharged.

In the illustrative embodiment, the switching mechanism includes a set of switches for selectively connecting each of the capacitive elements to the capacitive load and a switch control mechanism for selectively activating the switches.

## BRIEF DESCRIPTION OF THE DRAWINGS

FIG. 1 is a simplified representation of a conventional driver for a capacitive load.

FIG. 2 shows a system for charging the load capacitance by several steps and thereby reducing power dissipation.

FIG. 3 is a simplified schematic of a preferred embodiment of the circuit of the present invention for reducing the power dissipation of a capacitive load.

FIG. 4 is a diagram showing the control circuit of the driver constructed in accordance with the teachings of the present invention.

FIG. 5 is a timing diagram which illustrates the operation of the driver of the present invention.

## DESCRIPTION OF THE INVENTION

Illustrative embodiments and exemplary applications will now be described with reference to the accompanying drawings to disclose the advantageous teachings of the present invention.

While the present invention is described herein with reference to illustrative embodiments for particular applications, it should be understood that the invention is not limited thereto. Those having ordinary skill in the art and access to the teachings provided herein will recognize additional modifications, applications, and embodiments within the scope thereof.

Most of the power dissipation in digital CMOS circuits is due to repeated charging and discharging of capacitive loads including those internal to the circuit and those associated with the output signals.

FIG. 1 is a simplified representation of a conventional driver for a capacitive load. The load  $C_L$  represents the capacitance of a load and the interlead capacitance of the lines connecting the driver 10' to the load 12'. The load 12' is charged to the supply voltage  $V$  by connecting the load 12' to the power rail via a first switch 14'. In practice, the switch 14' may be a metal-oxide semiconductor field-effect transistor (MOSFET) which has a nominal "on" resistance. When the switch 14' is closed, a charge  $CV$  passes through the resistance of the switch 14'. The voltage drop across the resistance varies from an initial value of  $V$  to a final value of zero, so the average voltage drop  $V'$  traversed by the charge is  $V/2$ , if the capacitance is linear. The energy dissipated is:

$$E_{\text{diss}} = QV = CV(V/2) = CV^2/2$$

(1)

A similar argument applies to the discharge process, so a complete conventional charge-discharge cycle dissipates all the energy provided by the power supply,  $QV = CV^2$ .

In accordance with the present teachings, power dissipation is reduced by charging the capacitance of the load  $C_L$  in several steps. This is illustrated in FIG. 2.

FIG. 2 shows a system 10 for charging the load capacitance by several steps and thereby reducing power dissipation. Here, a bank of supply voltages  $V_1$  to  $V_N$  are used to charge the load 12. The voltages of the supplies are evenly distributed between ground and  $V_N$  so that the voltage difference between any two adjacent supplies is the same. Each of the voltages is selectively applied to the load 12 by  $N$  switches including the first switch 14 and  $N-1$  additional switches. Between charge cycles, switch 0 is closed. To charge the load, switch 0 is opened and the supplies  $V_1$  through  $V_N$  are connected to the load in succession by selectively closing the switches, that is, by momentarily closing switch 1, opening switch 1, momentarily closing switch 2 etc. To discharge the load, the supplies  $V_{N-1}$  through  $V_1$  are switched in in reverse order. Then switch 0 is closed connecting the output to ground.

If  $N$  steps are used, the dissipation per step is again given by the transferred charge and the average voltage drop across the switch resistance:

$$E_{\text{step}} = QV = (C/N) (V/N) = C^2/N^2 \quad (2)$$

To charge the capacitance all the way to the supply voltage  $V$ ,  $N$  steps are used, so the total energy dissipation is:

$$\begin{aligned} E_{\text{charge}} &= N \cdot E_{\text{step}} \\ &= N \cdot C^2/N^2 \\ &= CV^2/N \\ &= E_{\text{load}}/N \end{aligned} \quad (3)$$

Again, a full charge-discharge cycle will cause twice the dissipation of the charging only. Thus, according to this simplified analysis, charging by several steps reduces the energy dissipation per charge-discharge cycle and thereby the total power dissipation, by a factor of  $N$ .

The multiple supply voltages of FIG. 2 may be generated with a battery stack. For equipment not powered by batteries or when the desired voltage increment is not a multiple of the battery cell voltage, a power supply unit would seemingly have to generate these multiple supply voltages with an associated cost in expense, complexity and power dissipation.

FIG. 3 is a simplified schematic of a preferred embodiment of the circuit of the present invention for reducing the power dissipation of a capacitive load. The circuit 100 is essentially identical to that of FIG. 2 with the exception that the supplies  $V_1$ - $V_{N-1}$  are replaced with a corresponding number of capacitors  $C_T$  18 which will be referred to as "tank" capacitors. Each tank capacitor  $C_T$  has a capacitance which is much, much larger (e.g. an order of magnitude) than the load capacitance  $C_L$ . Switch operations are sequenced by a control circuit 20.

FIG. 4 is a diagram showing the control circuit 20 interconnected to plural MOSFET switches for an  $N=6$  implementation of the driver constructed in accordance with the teachings of the present invention. In FIG. 4, the tank capacitors 18 are eliminated for simplicity. The control signals may be provided by the circuit 20 or may be supplied by a host microprocessor. The control circuit 20 may be implemented in several configurations. For example, the control circuit may be implemented with a microprocessor or with a shift register and a counter. In the alternative, a latch 22 and input and output logic circuits 24 and 26, respectively, may be used as shown in FIG. 4. The input and

output logic circuits may be designed by a computer aided logic design program of which several are currently available. If a computer aided logic design program is used, the desired outputs would be specified in response to the expected input signals. The program would then design the logic circuits.

Timing signals are provided by a system clock (not shown) through the latch 22. In practice, the clock rate should be at least  $(N+1)$  times the output signal rate. In the preferred embodiment, switches 0-4 are implemented with n-channel MOSFET devices. Switches 5 and 6 are implemented with p-channel devices.

FIG. 5 is a timing diagram which illustrates the operation of the driver 100 of the present invention. In FIG. 5(a), the clock pulses are shown. The input signal is shown in FIG. 5(b). FIGS. 5(c)-(i) show the controls for switch 0-6 and FIG. 5(j) shows the output at the load  $C_L$ .

The operation of the circuits of FIGS. 3 and 4 is essentially the same as that of FIG. 2. That is, in the initial standby condition switch 0 is closed and there is no charge on any of the capacitors in the system. Next, when an input pulse is to be transferred to the load, switch 0 is opened and switch 1 is closed. Since there is no charge on the load,  $C_L$ , nor on any of the tank capacitors  $C_T$ , there will be no charge transfer through any of the switches as each is closed, in turn, momentarily. When the first switch 14 is closed, a charge is applied to the load 12.

On the trailing edge of input pulse, a discharge cycle is initiated by when the switches are momentarily closed in reverse order. Thus, switch N is opened and switch N-1 is closed. Then switch N-1 is opened and switch N-2 is closed and etc. On the closure of switch N-1, the associated tank capacitor will receive most of the charge on the load capacitance. Each capacitor down the line will receive a lower charge than the immediately preceding capacitor. After switch 1 opens, switch 0 closes to complete the cycle dumping the remaining charge on the load  $C_L$  to ground. Thus, over several cycles the tank capacitors will approach their steady state voltages, for example, the (N-1)th through 1st tank capacitors may have charges of say 5, 4, 3, 2 and 1 volts respectively. Then, at the beginning of the next cycle, on the closure of the first switch, the voltage on the first tank capacitor is applied to the load, then the voltage on the second capacitor is applied to the load and so on. Thus, in the example, first 1 volt is applied to the load, then 2 volts, then three volts and etc. As a result, the voltage on the load will gradually increase as shown in FIG. 5(j).

The circuits of FIG. 3 and 4 will provide the same power dissipation reduction as that of FIG. 2, but without multiply supply lines and without complicating the power supply. This is illustrated by the following analysis. Assume that each tank capacitor  $C_T$  is charged to the voltage of the corresponding supply of FIG. 2, and that the load capacitance  $C_L$  is discharged. The load capacitance is charged by closing and opening switches 1 through N in succession. Each tank capacitor (and the power supply) delivers a charge given by:

$$C_T V_N$$

[4]

Since the tank capacitors are much larger than the load, the tank voltages do not change significantly, so the dissipation in the switches will be the same as for the case in FIG. 2, where the supply voltages are constant. To discharge the load capacitance, switches N-1 through 0 are closed and opened in succession. During the discharge, each tank capacitor receives a charge of the same size as that delivered during charge phase, and an equally sized charge is dumped

to ground via switch 0. Over the full charge-discharge cycle, only the power supply injects any charge into the circuit. No net charge is drawn from any tank capacitor, so the tank voltages do not change.

The voltages of the tank capacitor bank are self-stabilizing. To appreciate this, assume that the voltage of one of the tank capacitors is slightly higher than it should be. Then, the charge delivered by this tank capacitor during the charging of the load will be somewhat larger than that given by equation (4), since the "step" from the voltage below is now slightly larger. During the discharge phase, the step from the voltage above is slightly smaller and the charge received is therefore smaller as well. Therefore, over the full cycle, a net decrease of the charge on the storage capacitor occurs, which causes a decrease in the capacitor voltage. The initial deviance is automatically counteracted.

Even if the tank capacitor voltages differ from the "correct" values, the circuit will work logically correctly, since each charging (discharging) cycle ends by connecting the load to the supply rail (ground). Voltage deviations simply bring higher dissipation. This happens during start-up, before the tank voltages have had time to converge to the even distribution between the supply voltage and ground.

The implementation cost of a driver such as that shown in FIG. 3 is determined by the tank capacitors, the switches, the mechanism controlling the switches, and the interconnections of same. Note that all extra interconnections are local. As for the conventional case, only one connection to the power supply is needed. Also, several drivers may share the same capacitor bank and part of the control mechanism.

The problem of maintaining the appropriate voltages on the tank capacitors is obviated by the fact that the capacitor voltages will converge automatically to the desired voltages. No additional circuitry is required. Only one supply line must be routed to the chip and the power supply need not be any more complicated than a conventional supply. In practice, the tank capacitors would be located off-chip.

For a CMOS implementation, the following design procedure may be followed to provide a driver configuration which exhibits minimal power dissipation.

Equation [3] indicates that dissipation decreases monotonically with increasing  $N$ . The number  $N$  cannot, however, be usefully made arbitrarily large because each step requires that a switch be turned on and off, which itself causes dissipation. Also, the energy used to drive each switch depends on the width of the device, which should be just enough to allow the charging to complete before the next step commences. Thus, for a given total allowable charging time  $T$ , there is an optimal number of steps and a set of optimal device sizes which lead to minimal total dissipation determined as follows.

Again, consider the circuit in FIG. 3 and assume the gates of the switch devices are driven conventionally. The load is charged and discharged once; the energy needed to drive the gates of the switch devices is:

$$E_g = \left( \sum_{i=1}^N C_i + \sum_{i=0}^{N-1} C_i \right) V^2 \quad (5)$$

Allot each step one  $N$ th of the total charging time  $T$ . Then:

$$T/N = mR_i C_i \quad (6)$$

Here,  $m$  is the number of RC time constants spent waiting for each charging step to complete. From equation [6], it is evident that all the switch devices should have equal on-resistance:  $R_i = R_{on}$ . Decreasing the on-resistance of device  $i$

00750501 014001

BEST AVAILABLE COPY

by increasing the width means increasing the gate capacitance:

$$R_i C_i = p_i \quad (7)$$

$p_i$  is a quality measure of the switch. It varies with  $i$ , since the bulk-to-channel and gate-to-channel voltages are different for different switches. Combining equations [5], [6], and [7] yields:

$$E_{\text{sw}} = \frac{Nm}{T} \left( \sum_{i=1}^N p_i + \sum_{i=0}^{N-1} p_i \right) C_L V^2 \quad (8)$$

Introducing  $\bar{p}$ , a weighted average of  $p_i$  for the different switches:

$$\bar{p} = \frac{1}{2N} \left( \sum_{i=1}^N p_i + \sum_{i=0}^{N-1} p_i \right) \quad (9)$$

If  $N$  is sufficiently large,  $\bar{p}$  is close to the unweighted average of  $p$  over the entire voltage range. Combining equations [3], [8] and [9] yields the following expression for the total energy dissipation:

$$E_{\text{tot}} = \left( \frac{1}{N} + 2N^2 \frac{\bar{p}}{T} \right) C_L V^2 \quad (10)$$

The number  $N$  that minimizes  $E_{\text{tot}}$  is given by:

$$N_{\text{opt}} = \sqrt[3]{\frac{T}{4m\bar{p}}} \quad (11)$$

The corresponding energy dissipation is:

$$E_{\text{opt}} = \frac{3}{2} \sqrt[3]{\frac{4m\bar{p}}{T}} C_L V^2 \quad (12)$$

It remains to select the value for  $m$ . If it is chosen too small, there will still be a significant voltage across a switch when the next switch is to close. Hence, there is an increase in the average voltage across each switch and therefore a dissipation increase (the first term in equation [10] is changed slightly). If on the other hand,  $m$  is chosen unnecessarily large, time is wasted that could have been used to increase the number of steps. Thus, in general, optimization methods for the value of  $m$  vary according to the application, however, one skilled in the art will be able to select a suitable value for  $m$  using conventional teachings (e.g., a simulation program).

By using the number of stages given by equation [10], the designer can minimize the power dissipation of the driver. The minimum is rather shallow, however, so a lower  $N$  (as would most often be dictated by practical considerations) will still give a considerable improvement over the conventional case;  $N=2$  already gives almost 50% reduction. Once  $N$  and  $m$  have been selected, the on-resistance of each switch is given by equation [6]. The corresponding gate capacitance, and thereby the width of the device, is given by equation [7]. The values of  $p$  for a certain process can be found by circuit simulation or by measuring the on-resistances of test devices of known widths.

Thus, the present invention has been described herein with reference to a particular embodiment for a particular application. Those having ordinary skill in the art and access to the present teachings will recognize additional modifications applications and embodiments within the scope

007531-0100

BEST AVAILABLE COPY